PRACTICAL CONTROL SYSTEM FOR CLASSROOM AND LABORATORY

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Abstract:

A practical control system (in which students test the fundamental blocks or the whole system) is a useful tool for enhancing understanding in the classroom or laboratory. Control systems built for training purposes are not widely available.

This paper presents elements of the design, construction and testing of an electro-mechanical control system. The system is easily built, and provides excellent results. Only basic instruments are required to monitor and measure control system characteristics. The system consists of the plant, the sensor, the comparator, the Proportional-Integral-Differential (PID) controllers, and the disturbance. The plant is a motor-driven fan and the output variable is the fan speed. The fan speed is monitored with a frequency counter. The system can be operated in an open-loop mode allowing students to measure the transfer function of the subsystems. The integral and differential controllers, as well as the disturbance, can be switched in or out of system. All control system characteristics can be observed and demonstrated. The effects of controllers on the system characteristics can be measured. A suggested list of laboratory experiments and their objectives is also included.

Introduction:

A control system is defined as an electronic/electrical/mechanical system used to automatically control, maintain and track a physical variable or system output. Most students have difficulty in identifying the control system. Before the system theory is developed, it would be much clearer in the student's mind if he sees an actual control system.

System design

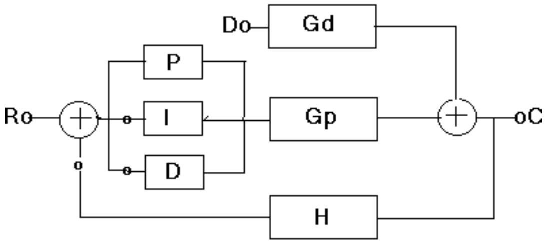

Fig.1 Block Diagram of System

The block diagram of a control system is shown in Figure 1. It consists of the plant, the sensor, the comparator, the PID controllers and the disturbance. Operational amplifiers are used as a gain block in most subsystems. The system can be operated in an open-loop or closed-loop mode. The Integral (I) and Differential (D) controllers as well as the disturbance can be switched in or out of the system. The input step voltage is generated within the system for testing purposes.

Figure 2 shows the plant and disturbance wiring diagram. The plant is a small armature-controlled DC motor-driven fan. The output variable is the fan speed expressed in Hz which can be monitored with a frequency counter. A DC power amplifier with gain buffers the plant and the controllers. An optical coupler is used to convert the fan speed in revolution per minute (rpm) to frequency in Hz. A square-wave voltage is generated when the seven fan blades interrupt the optical beam seven times per revolution giving a proportional constant of 7/60 (Hz/rpm). The transfer function $G_P(s)$ of the plant is approximated with a first order function, and measured using the step response method.

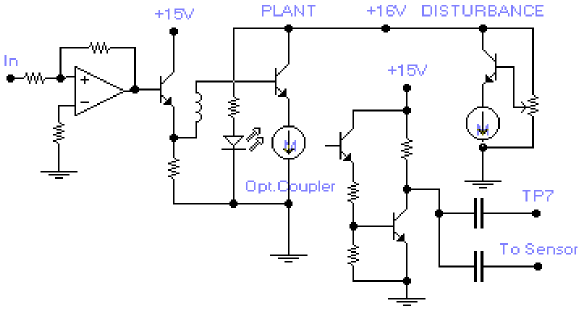

Fig.2 The Plant and Disturbance

$$G_P(s) = \frac{K_M}{s\tau_M + 1}$$

where
$K_M = 140\text{Hz/V}$
$\tau_M = 0.65\text{sec}$

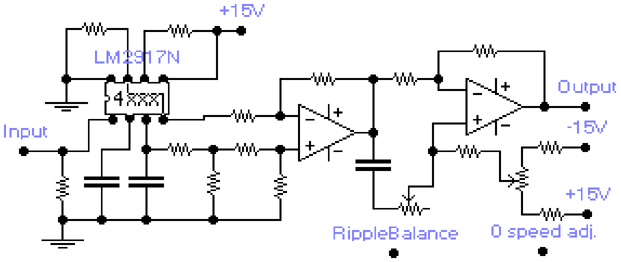

Fig. 3 Sensor

Figure 3 shows the circuit diagram of a sensor. It consists of an ac amplifier, frequency-to-voltage converter (FVC) and a DC amplifier with null and ripples balance adjustments. The FVC and the DC amplifier provide an output voltage approximately equal to 1V for an input frequency of 250 Hz, thus giving a proportional constant K_H of 0.0035 V/Hz. The transfer function of the sensor is approximated with a first order function, and measured using the step response method. A step change of square-wave frequency is applied to the ac amplifier. The output of a sensor is a step response. The time constant τ_M comes from the RC circuit in the FVC. Below is sensor transfer function H(s).

$$H(s) = \frac{K_H}{s\tau_H + 1}$$

where
$K_H = 0.0035\text{V/Hz}$
$\tau_H = 0.065\text{sec}$

Figure 4 shows the circuit diagram of comparator and PID controllers. The comparator is a two-input unity gain amplifier. The Proportional controller (P), which is permanently connected to the system, uses two operational amplifiers providing a maximum gain of 50. The gain is adjustable from 0.5 to 50 with a switch and a

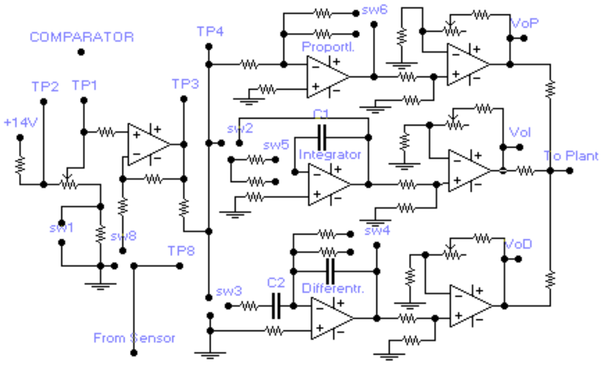

Fig. 4 Comparator and PID Controllers

potentiometer. The Integral controller (I) also uses two operational amplifiers providing an adjustable gain from 0.5 to 50 with a switch and a potentiometer. It can be switched in or out of the system. Similarly, the Differential controller (D) uses two operational amplifiers providing an adjustable gain from 0.5 to 50 with a switch and a potentiometer. It can be switched in or out of the system. The respective transfer functions of the controllers are the following:

$P(s) = K_P$ where $0.5 \leq K_P \leq 50$
$I(s) = K_I/s$ $0.5 \leq K_I \leq 50$
$D(s) = s\,K_D$ $0.5 \leq K_D \leq 50$

The disturbance is also a motor-driven fan with variable speed facing and opposing the plant.

System Performance

The closed-loop system transfer function is:

$$T(s) = \frac{G_C G_P}{1 + G_C G_P H} = \frac{9.1 G_C (s + 15.4)}{(s+1.54)(s+15.4) + 11.61 G_C}$$

CH. EQ. :$(s + 1.54)(s + 15.4) + 11.61 G_C = 0$

Step response

With only a proportional controller, the step response varies from over-damped to under-damped for K_P between one and five. The step response is critically damped for $K_P = 4.13$.

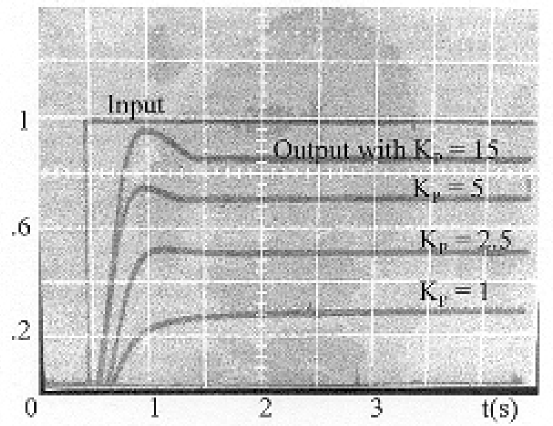

Fig.5 Step response with different K_P

$K_P = 2$	Over-damped	OS =0%	e_{SS} =50%
$K_P = 4$	Critic.-damped	OS =0%	e_{SS} =33%
K_P =15	Under-damped	OS =8%	e_{SS} =12%

The actual system step response is shown in figure 5 for different values of K_P. The steady state error can also be observed in this graph.

Steady state error

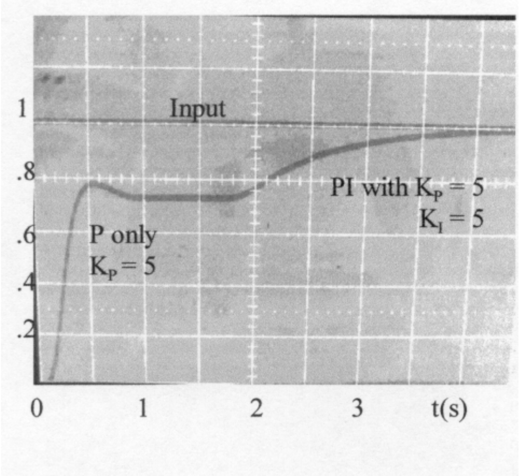

Fig. 6 Steady error with P and PI

The steady state error due to a step input exists for a system having only a proportional controller. The error decreases with the increase of proportional controller K_P. The actual error is shown in figure 5 for different values of K_P used in the system. There is no steady state error for type one system. The system changes to type one when the Integral controller K_I/S is inserted. Figure 6 shows the steady state error for the system with P only and with PI.

Disturbance

The disturbance affects the steady state error for type zero system. The system changes to type one when an integrator is added. The error is reduced to zero. Figure 7 shows the actual system response before and after the presence of the disturbance. Initially, the system is operated with only a proportional controller having a small value of K_P. It is purposely chosen to show the effects of the disturbance on the steady state error. When the integrator having K_I equal to five is inserted, the steady state error is reduced to zero.

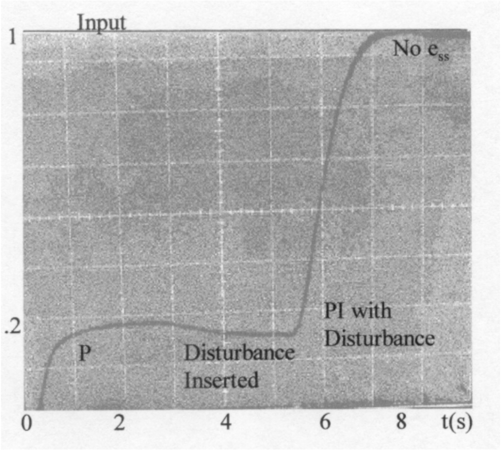

Fig.7 Disturbance effects on e_{SS}.

Stability

This system is unconditionally stable if only the Proportional controller is used. There are only two poles in the closed-loop system transfer function. However, it can become unstable if it uses the PI controller which adds a third pole to the system. The Routh-Hurwitz criteria show that the system becomes unstable when the ratio of K_I to K_P exceeds 50. Figure 8 shows two step responses with $K_I/ K_P = 60$ and 40. The system response to a step function becomes oscillatory for $K_I/ K_P = 60$.

The differential controller (D) adds a zero to the transfer function of the system. It helps to speed up the system. The system becomes more stable. Figure 9 shows two step responses of the system with PI and PID.

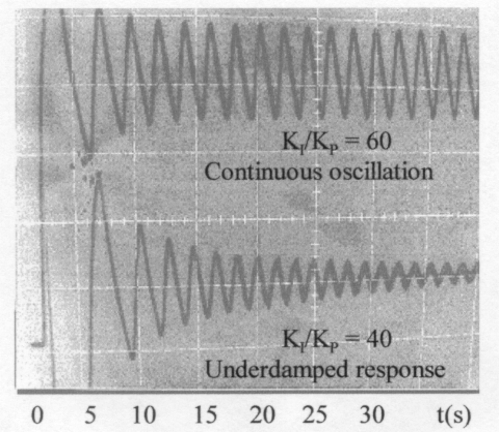

Fig. 8 Stability of system with PI

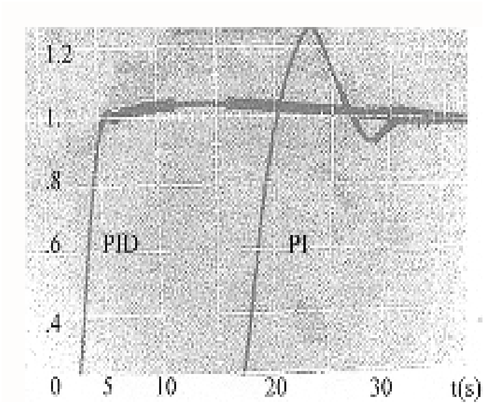

Fig. 9 Step response with PID and PI

A photograph of the actual control system is shown in figure 10.

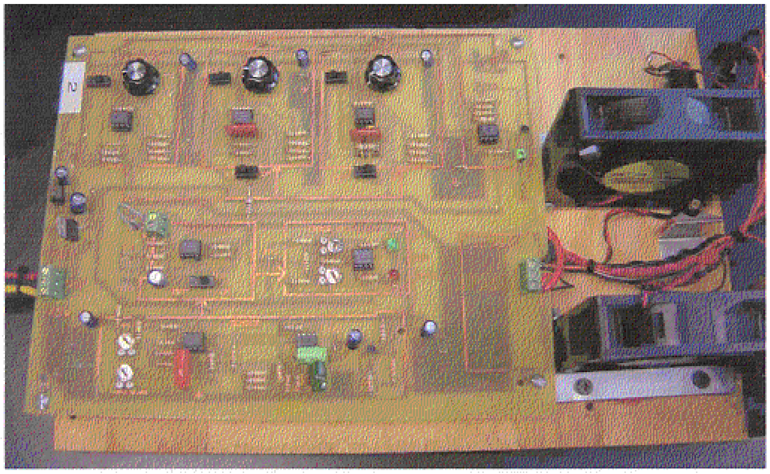

Fig.10 Control System

List of Hardware

Motor-driven Fans:
2- 12VDC/.35A DC Motor with 7-blade fan
Integrated Circuits:
8- LM258 - Dual op. Amp. 1- LM2917- Freq-to-Volt Convertor
Transistors
4- 2N3904- NPN 2- IP122 - Power
Miscellaneous Active Components
1- LM7815 -15V Pos. Regulator 1- LM7915 -15V Neg Regulator
1- NTE3034 Photodetector 1- 1W miniature incandescent lamp
Capacitors 1- Electro.10μ/25V 1- Electro.33μ/50V 4- Ceram.1μ/25V
1- Ceram.0.47μ/25V 1- Ceram.0.22μ/25V 1- Ceram.10n/25V 1- Ceram.1n/25V
Resistors (All 1/2W)
1- 51 1- 330 1- 560 1- 750 6-1K 1-2.2K 2- 5.1K 1- 5.6K 17-10K
4- 33K 1- 39K 2- 47K 16-100K 1-200K 2-470K 2- 2M 1- 4.7M
Inductor 1- 1mH
Trimpots 2- 1K 1- 5K 1- 25K 1- 100K
Potentiometers 2- 500 3- 100K
Miscellaneous Parts
6- DPDT PB Slide Switches 1- SPST PB Momentary Switch 2- LED (red, green)
2- Power connectors

Descriptions of the experiments

1. Identify and measure the transfer functions of control subsystems. The transfer function of the plant, the sensor and the PID controllers are measured using the step response method, with either the external signal source or the step function generated in the system.
2. Formulate the closed-loop system transfer function.
3. Study the performance of system, open-loop and closed-loop systems, with respect to the speed of response. Observe and measure the characteristics of open-loop system. Observe and measure the effects of controllers P, PD., PI and PID on the speed of response of closed-loop system.

4. Study the performance of system, open-loop and closed-loop systems, with respect to the steady state error and disturbance rejection. Observe and measure the effects of controllers P, PD., PI and PID on the steady state error and disturbance of closed-loop system.
5. Study and predict the stability of the system. Theoretically, this control system is unconditionally stable if it does not used PI controller. However, the system can become unstable if PI controller is used. Observe and measure the effects of controllers P, PD., PID and PI on the system stability.
6. Design a control system meeting certain performance criteria. For example, design a control system to meet the following requirements: speed of response $\tau = 0.1$s, % OS $\leq$ 5%, $e_{SS} \leq$ 1% and stable system.

Conclusions

The basic electro-mechanical control system can be easily built and yield good results. It requires only basic instruments to monitor and measure the system characteristics. The system can be used in the classroom for demonstration while system theory is being developed, or in the laboratory to perform experiments.

The first time users have a difficulty with the first experiment. It measures the transfer function of subsystems and requires a test signal such as a step change of square-wave frequency from the external source to apply to the system. Students seem to like experimenting with the system after they get through the first experiment.

DC amplifiers are used as a gain block in most subsystems. Their output offset voltage contributes to the system steady state error. The output stage of the FVC requires zero-speed adjustment periodically. Ten millivolt offset will introduce approximately 1 percent error on the steady state. The DC supplies to the motors and the rest of the electronic circuits must have separate voltage regulators. The back emf from the motors will interfere the electronic circuits through the power supply. The differential controller is a high frequency amplifier. It reacts to any fast change of signals such as the back emf voltage and the residual ripple in the FVC circuits. A sensing circuit can be added to the system to detect the error signal for visual display. Two LEDs, a red and a green, light up alternately or go out simultaneously indicating the magnitude and sign of an error signal during the transient and steady state response.

Acknowledgments

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